BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B71 01010

SUBJECT: Effects of LM Descent Propellant Gaging Inaccuracy on Propellant Budgeting - Case 310

DATE: January 12, 1971

FROM: K. P. Klaasen

ABSTRACT

For effective mission planning, spacecraft propellant should be budgeted as closely as possible to the way in which it will actually be used in flight. Although this principle has been followed in general in LM descent budgeting (for example, in allocating propellant to cover the abort reserve requirement and the effects of propellant sloshing), it has not been followed in allocating propellant to cover DPS propellant gaging inaccuracies. At present, the operational rules and the budgeting rules are inconsistent in their treatment of gaging inaccuracies. Operationally the gaging uncertainties are simply subtracted from available DPS burn time, while in propellant budgeting the gaging uncertainties are treated as dispersions and are root-sum-squared with other uncertainties. The effect of this inconsistency on DPS performance is to reduce the actual available burn time between planned manual takeover and touchdown from the pre-mission assumed value of 140 seconds to only 137 seconds in the case of a limit weight vehicle with 3σ low performance and sloshing propellant.

In order to properly make the two sets of rules consistent, the propellant budget should be changed to include (1) a new allocation that is equal to the gaging uncertainty and is subtracted from available propellant to correspond to the bias placed on available burn time operationally and (2) the current allocation in the dispersions to account for plus or minus gaging uncertainties. Such a change in budgeting philosophy would result in a 52-pound reduction in the LM limit weight for current values of the gaging uncertainties.

Either the DPS Low Level Sensor (LLS) or the Propellant Quantity Gaging System (PQGS) could be chosen in real-time as the indicator of remaining propellant. Propellant must be budgeted to cover the uncertainties of only the more accurate of these gaging systems.

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DATE: January 12, 1971

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MEMORANDUM FOR FILE

Inconsistency in the Treatment of Low Level Sensor Inaccuracies

To assist in effective mission planning, spacecraft propellant should be budgeted before the mission as closely as possible to the way in which it will actually be used in flight. In general, this budgeting principle has been applied in allocating LM descent propellant. The reductions in usable propellant that result from the required abort reserve propellant and from the expected sloshing of propellant have been accounted for by proper allocations in the budget. However, in budgeting propellant to cover for the effects of propellant gaging inaccuracy, the above principle has not been applied faithfully. The budgeting rules in this case are not consistent with the operational rules governing the use of low-level propellant gaging information.

On past missions, the DPS Low Level Sensor (LLS) was the prime real-time indicator of DPS propellant remaining during the final portion of descent. According to the Spacecraft Operational Data Book[1], 116±3 seconds of DPS burn time remains when the LLS is activated if it is assumed that there is no propellant sloshing. The 3-second uncertainty results from an uncertainty in the location of the LLS in the propellant tanks. Apollo 13 mission rules[2] allowed 93 seconds from LLS activation until the touchdown/abort decision point. This 93 seconds corresponds to the nominal 116 seconds of burn time minus 3 seconds for uncertainty in LLS location minus a 20-second abort reserve.

Figure 1 shows the current J-1 mission descent propellant budget as listed in the MSC weight summary[3] and a breakdown of the dispersions. The 48-pound allocation in the budget for the LLS represents 5 seconds of burn time that is set aside to cover for propellant sloshing. Sloshing propellant tends to

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[1]"Volume II LM Data Book - Appendix LM-6," Grumman Aerospace Corporation, November 13, 1969.

[2]"Final Flight Mission Rules - Apollo 13," Manned Spacecraft Center, February 12, 1970.

[3]"Apollo Spacecraft Weight Status Summary," Manned Spacecraft Center, December 15, 1970.

BUDGET

Tanked Propellant	19,509 lbs.
Trapped and Residual	-55
Outage	-37
Usable Propellant	19,417
3σ Dispersions	-321
Low Level Sensor	-48
Abort Reserve	-191
Available for Delta-V	18,857
Required for Delta-V	-18,762
Excess Propellant	95

DISPERSIONS

Fuel Loaded	8 lbs.
Oxidizer Loaded	29
Fuel Trapped	0
Oxidizer Trapped	36
I_{sp}	128
Thrust and Navigation	257
Separation Weight	20
Consumables	9
Mixture Ratio	132
Low Level Sensor Location	28
RSS	321

FIGURE 1 - J-1 MISSION LM DESCENT PROPELLANT BUDGET AND DISPERSION BREAKDOWN

activate the LLS prematurely causing the gage to indicate that less propellant remains in the tanks than is actually there. Since it cannot be known in real time whether or not sloshing has caused the LLS to be activated prematurely, the gage reading must be assumed to be correct, and propellant must be set aside and called unusable to allow for an early LLS activation due to slosh. The allocation of 28 pounds (equivalent to 3 seconds of burn time) in the dispersions accounts for the uncertainty in LLS location. Root-sum-squaring all the dispersions yields the 321-pound allocation in the budget.

The inconsistency between operational rules and budgeting rules involves the handling of the 3-second uncertainty in LLS location. The operational rules call for subtraction of the 3 seconds from available burn time while the budgeting rules require that the 3 seconds be root-sum-squared with many other dispersions before being subtracted from the usable propellant thereby making its effect on the amount of propellant available for delta-V nearly negligible ($\approx$1 pound). The difference between the two sets of rules causes 3 seconds less burn time to be available during the actual descent than was expected to be available before the mission (if dispersions are assumed equal).

Effects of Inconsistency on LM Descent Performance

An inconsistency that causes a 3-second reduction in available burn time has a major effect on descent performance. Since past missions have all had substantial excess DPS propellant, the 3-second decrease in operational burn time has had little effect on actual performance. However, for a limit weight vehicle with 3σ low performance and sloshing propellant, the 3 seconds lost is very real and could conceivably result in the loss of a LM landing. In this case, only 137 seconds of burn time is available from planned manual takeover to touchdown rather than the 140 seconds assumed in mission planning. From an alternative viewpoint, if the 3 seconds of burn time were subtracted from usable propellant in the pre-mission budget as it is in the operational rules, the LM limit weight would be reduced by 52 pounds. As shown in a recent spacecraft weight summary,[4] for the J-1 mission the current LM limit weight exceeds the current control weight by only 76 pounds and exceeds the present actual LM weight by only 185 pounds. The existing inconsistency between operational rules and propellant budgeting rules, therefore, creates a somewhat false sense of security since the descent burn time available is actually 3 seconds less than the difference between the current LM weight and the current LM limit weight would indicate.

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[4]"Apollo Spacecraft Weight Status Summary," Manned Spacecraft Center, December 15, 1970.

Elimination of the Inconsistency

In order to eliminate the potential 3-second reduction in available LM descent burn time and to make the propellant budget correspond to the way in which propellant will actually be used in flight, the operational rules and the budgeting rules should be made consistent. In making the rules consistent, the problem is to determine which (if either) set of rules is the correct one to use. The basic principle behind the current operational rules is that the propellant gaging system should never indicate more propellant than is actually in the tanks.* Therefore, the Apollo 13 rules assumed that only 113 seconds (116 seconds nominal minus 3 seconds dispersion) were available for use after the LLS was activated in order to allow for a sensor that was located 3σ too low in the tanks. Adherence to the above principle is necessary to insure that propellant depletion not occur before the crew expects it. Thus, the practice of subtracting uncertainties in propellant gaging from the nominally available burn time as is done in the operational rules is a reasonable one. The pre-mission propellant budgeting should also follow this practice.

The major purpose of propellant budgeting is to determine the quantity of propellant that is available for use in providing delta-V. Inaccuracies in propellant gaging cause some propellant to become unavailable for use. To determine how much propellant must be set aside as unavailable due to uncertainties in propellant gaging, the various circumstances that could cause the gage to indicate a quantity different from that actually in the tanks must be considered, and the amount of available propellant lost in each case must be determined. Figure 2 lists the possible LLS propellant gaging inaccuracies and their effects on available propellant assuming that operational rules follow the principle that the gaging system should never indicate more propellant than is actually in the tanks. Since in real time the true circumstances affecting LLS propellant gaging are unknown, the operational rules must allow for the worst case (i.e., the case with the least burn time actually remaining at LLS activation) which occurs with a 3σ low LLS location in the tank and no propellant sloshing. If no sloshing occurs and the LLS is activated at the nominal time, 3 seconds of available burn time is made unavailable because of the operational rules. If the LLS is located 3σ high in the tanks and comes on early with no propellant slosh, a total of 6 seconds of available burn time is lost.

The effects of LLS inaccuracies on available burn time subject to the given operational rules can be described by a biased normal distribution as shown in Figure 3. For no propellant sloshing, the 3-second bias in available burn time between the value at LLS activation according to the operational rules and the actual value

*"Never" actually means a probability of 1-.99865 = .00135.

Inaccuracy	Effects	Reduction In Available Burn Time
LLS located 3σ too low in tank. No propellant sloshing.	3 secs. more burn time than nominal used before LLS activation. 113 secs. burn time actually left after LLS activation. Operational rules allow use of 113 secs. burn time after LLS activation.	0 secs.
LLS located nominally in tank. No propellant sloshing.	0 secs. more burn time than nominal used before LLS activation. 116 secs. burn time actually left after LLS activation. Operational rules allow use of only 113 secs. burn time after LLS activation.	3 secs.
LLS located 3σ too high in tank. No propellant sloshing.	3 secs. less burn time than nominal used before LLS activation. 119 secs. burn time actually left after LLS activation. Operational rules allow use of only 113 secs. burn time after LLS activation.	6 secs.
LLS located 3σ too low in tank. Propellant slosh activates LLS 5 secs. early	2 secs. less burn time than nominal used before LLS activation. 118 secs. burn time actually left after LLS activation. Operational rules allow use of only 113 secs. burn time after LLS activation.	5 secs.
LLS located 3σ too high in tank. Propellant slosh activates LLS 5 secs. early.	8 secs. less burn time than nominal used before LLS activation. 124 secs. burn time actually left after LLS activation. Operational rules allow use of only 113 secs. burn time after LLS activation.	11 secs.

FIGURE 2 - EFFECTS OF VARIOUS LLS PROPELLANT GAGING INACCURACIES ON AVAILABLE BURN TIME

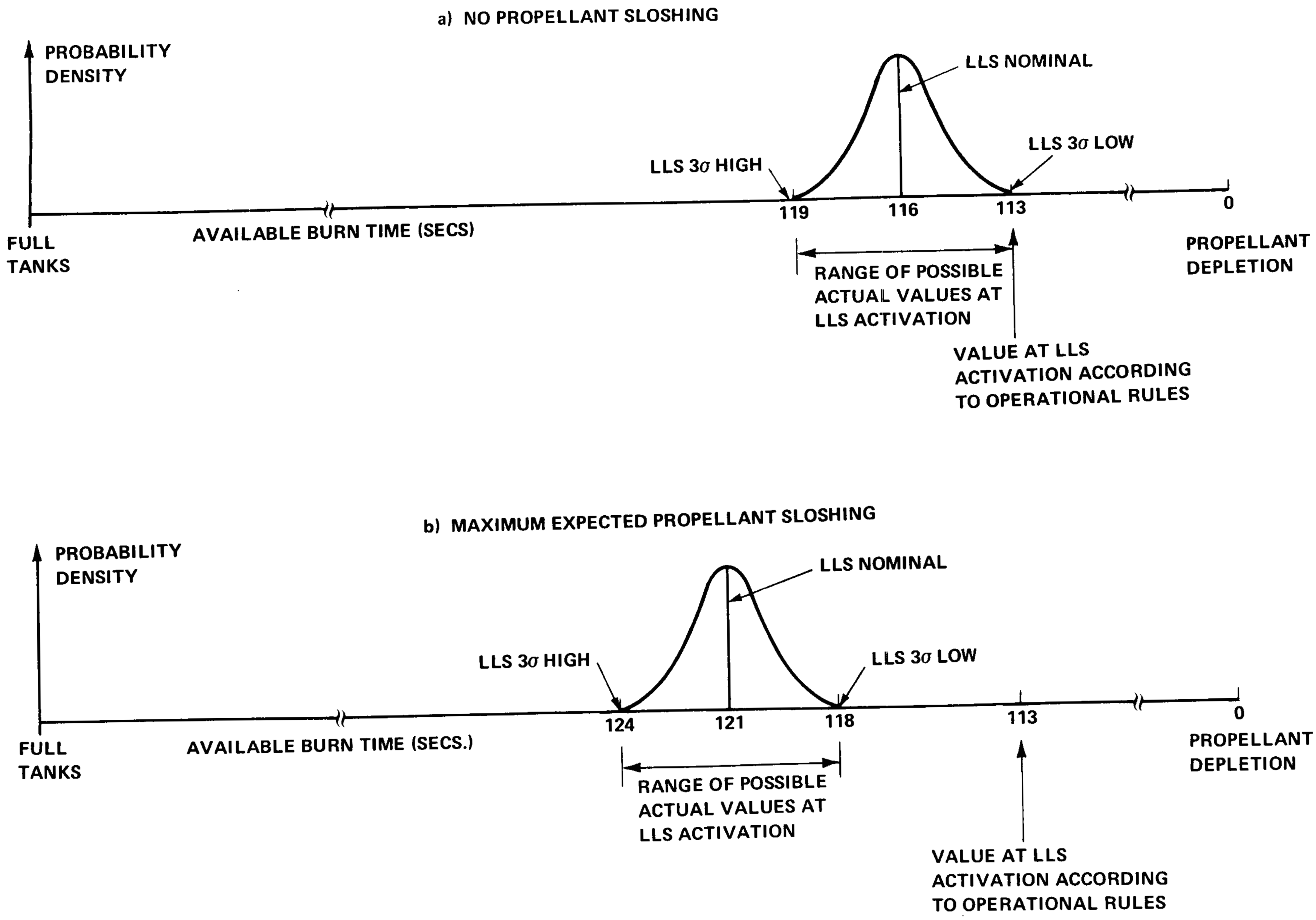

FIGURE 3 - EFFECTS OF LLS PROPELLANT GAGING INACCURACY ON AVAILABLE BURN TIME SUBJECT TO GIVEN OPERATIONAL RULES

for an accurate LLS corresponds to the 3 seconds of burn time subtracted from the nominal amount at LLS activation in the operational rules, and the 3σ deviation of the normal distribution is the 3-second uncertainty in LLS location. The effect of propellant sloshing is to increase the bias by 5 seconds since it has the same effect on available burn time as a high LLS location.

In the current budget, the 5-second bias due to propellant slosh and the 3-second uncertainty in LLS location have been accounted for. However, the 3-second bias in available burn time caused by the operational rules has not been accounted for. Therefore, to properly budget the propellant that is made unavailable by LLS inaccuracies, an additional allocation of 28 pounds (3 seconds of burn time) should be made in the budget to correspond to the 3 seconds subtracted from available burn time operationally. The 48-pound allocation for LLS inaccuracy due to propellant slosh should remain in the budget, and the 28-pound dispersion due to LLS location uncertainty should remain in the dispersions.

Treatment of Propellant Quantity Gaging System Inaccuracy

The problem of properly budgeting propellant to allow for uncertainties in gaging becomes somewhat more complicated for future missions because of forthcoming changes to the operational rules. Rather than using only the LLS as prime indicator of remaining propellant, both the LLS and the Propellant Quantity Gaging System (PQGS) will be used in the future. Telemetry from both systems will be received in the Mission Control Center in Houston. At the time of LLS activation, a display in Mission Control showing burn time remaining to the touchdown/abort decision point will begin counting down from 93 seconds (116 seconds nominal minus 3 seconds LLS uncertainty minus 20 seconds abort reserve). PQGS data will also be received and smoothed to eliminate the effects of propellant slosh. At the time when the PQGS reading reaches 5.6% propellant remaining (the quantity at which the LLS would nominally be activated), a display of burn time remaining to the touchdown/abort decision point will begin counting down from 88 seconds (116 seconds nominal minus 8 seconds PQGS uncertainty minus 20 seconds abort reserve). If both readings are reasonable, the higher reading will be used. Since both readings already have their 3σ uncertainties subtracted off in accordance with the principle that a gage will never indicate more propellant than is actually in the tanks, the higher reading must necessarily (99.865% of the time) be closer to the actual quantity and is, therefore, the proper one to use.

If the PQGS is the system to be used in a given case, some propellant will be made unavailable due to PQGS inaccuracy. This propellant should be accounted for in the pre-mission propellant budget. Figure 4 lists the possible PQGS propellant gaging inaccuracies and their effects on available propellant assuming that operational rules follow the principle stated above. Again operational rules must allow for the worst case, which is the case of the PQGS reading 3σ high. For an accurate PQGS reading, 8 seconds of available burn time is made unavailable because of the operational rules. If the PQGS reads 3σ low, a total of 16 seconds of available burn time is lost. Again the effects of PQGS inaccuracies on available burn time can be described by a normal distribution biased by 8 seconds with 3σ equal to 8 seconds.

Since either of the two gaging systems could be used as the real time indicator of remaining propellant, it must be decided which system inaccuracies to cover in the pre-mission propellant budget. Whichever system is chosen, enough propellant should be budgeted to cover for the lowest expected gage reading of that system below the actual quantity of propellant in the tanks. For the LLS, the lowest expected reading would be the actual amount minus 3 seconds for LLS uncertainty minus 5 seconds for propellant sloshing. For the PQGS, the lowest expected reading would be the actual amount minus 8 seconds for PQGS uncertainty. But the operational rules stipulate that the largest of the two gage readings will be used. Thus propellant has to be budgeted only for the system with the highest worst case reading in order to cover for the worst case gaging inaccuracy. In other words, if

$$3\sigma_{LLS} + \text{slosh allocation} \leq 3\sigma_{PQGS},$$

propellant should be budgeted for LLS inaccuracies, i.e., 48 pounds for propellant sloshing and 28 pounds for operational rules governing LLS usage should be subtracted from usable propellant and 28 pounds for LLS location uncertainty should be included in the dispersions. Propellant should be budgeted for LLS inaccuracies when the equality holds above because, for the worst case gage reading by each system, either reading could be used in real time, and budgeting for LLS inaccuracies leaves more propellant available for delta-V than budgeting for PQGS inaccuracy. If

$$3\sigma_{LLS} + \text{slosh allocation} > 3\sigma_{PQGS},$$

Inaccuracy	Effects	Reduction In Available Burn Time
Smoothed PQGS reads 3σ more propellant than is actually in the tanks.	8 secs. more burn time than nominal used before 5.6% indication. 108 secs. burn time actually left after 5.6% indication. Operational rules allow use of 108 secs. burn time after 5.6% indication.	0 secs.
Smoothed PQGS reads the same as the quantity of propellant actually in the tanks.	0 secs. more burn time than nominal used before 5.6% indication. 116 secs. burn time actually left after 5.6% indication. Operational rules allow use of only 108 secs. burn time after 5.6% indication.	8 secs.
Smoothed PQGS reads 3σ less propellant than is actually in the tanks.	8 secs. less burn time than nominal used before 5.6% indication. 124 secs. burn time actually left after 5.6% indication. Operational rules allow use of only 108 secs. burn time after 5.6% indication.	16 secs.

FIGURE 4 - EFFECTS OF VARIOUS PQGS PROPELLANT GAGING INACCURACIES ON AVAILABLE BURN TIME

propellant should be budgeted for PQGS inaccuracy, i.e., 76 pounds for operational rules governing PQGS usage should be subtracted from usable propellant and 76 pounds for PQGS inaccuracy should be included in dispersions. Since the current values of the relevant quantities are

$3\sigma_{LLS}$ = 3 seconds burn time,

slosh allocation = 5 seconds burn time,

$3\sigma_{PQGS}$ = 8 seconds burn time,

propellant should currently be budgeted for LLS inaccuracies.

Summary

For effective mission planning, propellant should be budgeted to correspond as closely as possible to the way in which it will actually be used in flight. Although this principle has been followed in allocating propellant to cover the effects of things such as sloshing propellant and the abort reserve, it has not been followed in the allocation for propellant gaging inaccuracy.

At present, the operational rules and the propellant budgeting rules governing LM descent are inconsistent in their treatment of propellant gaging inaccuracies. Operationally the gaging uncertainties are subtracted from available burn time, while in propellant budgeting the gaging inaccuracies are treated as dispersions and are root-sum-squared with other uncertainties. To make the two sets of rules consistent, the gaging uncertainties should (1) be subtracted from available propellant in the budget to correspond to the bias placed on available burn time operationally and (2) be included in the budgeted dispersions to account for plus or minus gaging uncertainties. Since either the LLS or the PQGS could be used in real-time as the indicator of remaining propellant, propellant must be budgeted only to cover the uncertainties of the most accurate of these gaging systems.

K. P. Klaasen

2013-KPK-jab K. P. Klaasen

BELLCOMM, INC.

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From: K. P. Klaasen

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